Performance-enhancement of Phase Change Materials for Energy Conservation in the Built Environment: A State-of-the-art Review

Quynh Thuy Nguyen
Department of Infrastructure Engineering, The University of Melbourne
(thuyqn@student.unimelb.edu.au)
Tuan Ngo
Dept. of Infrastructure Engineering, The University of Melbourne
(dtngo@unimelb.edu.au)
Priyan Mendis
Department of Infrastrure Engineering, The University of Melbourne
(pamendis@unimelb.edu.au)

Abstract

Energy conservation has become a critical issue in the world today as strong economic growth is unfeasible without a sustainable strategy of energy conservation. Apart from long-term environmental impact, a well-managed strategy for energy consumption even results in improvement of the financial performance in the short term. Phase change materials (PCMs) with its capacity of storing thermal energy as latent heat is a viable approach of the utilization of solar heat, a green source of energy, and the optimization of energy consumption in buildings. However, the obstacle that prevents PCMs from being applied widely in practice comes from its poor performance in terms of heat transfer and shape stabilization. This article, therefore, presents a critical review of PCM and effective methods to boost its performance in terms of shape stabilization and transient heat transfer.

Keywords: Phase Change Material, Energy consumption, Leakage, Thermal conductivity

1. Introduction

The civilization of the human kind began and has been side by side with energy. From the invention of fire – the dawn of energy thousands years ago, the development and growth of a 7-billion-individual society has been witnessed. However, the demand for energy has resulted in serious impacts such as overuse of natural resources and the green house emission, back to natural environment. The need of a strategy for the sustainability of energy system is, hence, necessary ever than before. Bonjenec and Papler (Bojnec and Papler, 2011) reveal the clear correlation between sustainable development, energy consumption and economic efficiency, which again asserts the certainty of sustainable energy nowadays.

Energy consumption is divided into three main groups of end-users, which are buildings (both residential and commercial), transportation and industry. The proportion of household-services in the national energy consumption of German is 42% (2011a), which is the largest sector in 2010. This number of Australia and Canada, which are countries with high demand of energy consumption, is 23% (2011b) and 31% (2010) respectively. In the US – the country with the highest consumption of global energy, the total energy consumed in the last 30 years increased by 28% while energy used in buildings (residential and commercial) climbed up by 58% (2011c). The latter also contributed to 41% of the total energy consumption in 2010. These figures insist that the demand for energy in buildings increases significantly. In addition, energy in buildings relates mostly to maintain the indoor condition in a comfort range for the occupants, thus it leads to the need of effective and environmental methods to prolong the thermal comfort in buildings.

Aiming at green technology for building energy conservation, conventional method with insulation materials such as cotton and fiberglass for the building envelopes has been investigated in the last decades. The purpose of the insulation material is to achieve higher thermal mass of the walls, floors or ceilings, however these materials accumulate a higher load to the construction and the more complex structure (Baetens et al., 2010). Therefore, scientists and researchers turn to another initiative: passive method of thermal storage for the constructive materials. Passive systems of energy storage utilize wind or solar energy, thus meet the requirement of energy savings and thermal comfort in modern buildings.

Thermal energy storage can be in the type of sensible heat or latent heat. Both sensible and latent heat methods are demonstrated to gain significant effect on reducing the operation energy for HVAC systems in buildings (Kuznik and Virgone, 2009), but the former insists higher amount of materials and various working temperature. Furthermore, system of sensible heat storage expresses effectiveness mostly when the condition is in its steady state (Esam M, 2008). So the strategy of latent heat thermal energy storage has been paid more attention to in recent years. The principle of latent heat storage is using phase change materials (PCMs) with melting/freezing temperature close to the range of thermal comfort. When the ambient temperature exceeds this point, the fluidity of PCMs absorbs heat from the ambient and conversely the solidification of PCMs desorbs heat in case the ambient temperature falls below freezing point. Nevertheless, PCMs have not been applied in practice widely because of two major drawbacks: leakage and low thermal conductivity. This article, hence,

gives an overview of available PCMs and the state-of-the-art solutions for enhancing the performance of PCMs to address the issue of energy conservation in the built environment.

2. Phase Change Materials: Fact and Figures

2.1. Mechanism of PCMs

As introduced briefly previously, phase change material uses this high capacity of heat transfer during its phase transition to store heat and help moderate the ambient temperature in human comfort condition. PCM is feasible in storing thermal energy in that particular way because of the endothermic/exothermic process of phase transition. In most cases, the embodied energy of a material in solid state is lower than in fluid, as a result, the transition from solid to liquid demands a certain amount of energy to accomplish. At the temperature of fluidity, the supplied energy is to change the connection between molecules to fluid phase and no increase in temperature is observed at this stage. Another constant temperature occurs in the solidification with the same cause but the excess energy is released.

This mechanism explains apparently why latent heat energy storage is superior compared to sensible method. For the latter, the capacity of heat storage depends on the specific heat capacity of the materials while for PCMs, this capacity include specific heat capacity and latent heat. In spite the specific heat capacity of PCM is not very high compared to other sensible heat storage material, its capacity of high latent heat dominates. Another advantage of PCMs from that mechanism is its small variation of temperature between storage interval and releasing heat interval.

In practice, PCMs help to minimize the heat flow between indoor and outdoor conditions as followed (Castell et al., 2010, Esam M, 2008): endothermic melting results in heat absorption during day time and exothermic freezing causes heat emission during night time. So PCMs assist with available energy system such as electricity to meet the annual demand of energy and less investment into HVAC system in buildings. This will be discussed further in the next part of the articles.

2.2. Effect of PCMs in energy conservation for buildings

The working principles of PCMs and its potential in application was regarded previously, this part of the article is to demonstrate quantitatively the effect of PCMs in building energy conservation.

Castell et al. (Castell et al., 2010) studies the impact of PCMs RT-27 in construction of brick and poly urethane. Figure 1 describes the structure of the tested sample, wherein RT-27 is applied in the vertical walls and the roof; a fluctuated temperature is applied on the outer surface of the sample. The study reveals that conventional brick sample consumes 9376Wh in 5 days, while sample with RT-27 and polyurethane uses only 3907Wh, which meant the decrease of 58%. This leads to a saving of 9.8 kg CO_2 emission annually for each square meter of the wall. In another study, Zhang et al. (Zhang et al., 2011) shows thermal respond of traditional brick wall without PCM and brick wall with 20.9% of PCM. Figure 2 is plotted the cross section of the wall after 30 hours exposure to fluctuated temperature. Several squares in the lower plot point the position of PCM in the brick wall. Beside the

effect of reducing temperature, the presence of PCM in brick wall also delay the inside heat transport owing to its phase change effect. Figure 3 comes from a recent study of Gracia et al. (de Gracia et al., 2011), wherein the rate of heat accumulation of gypsum sample with/without PCM is illustrated. In the first hour of heat exposure, both samples accumulate heat with the same rate but after peaking at 2.5W, the sample without PCM decreases the rate of heat accumulation until reaching its steady state after 12h as opposed to another peak in the case of the sample with 13.5% wt. PCM. Consequently, PCM increases the heat storage capacity by 30% and lengthens the thermal lag to 1.09h (i.e. increase by 1.2 times).

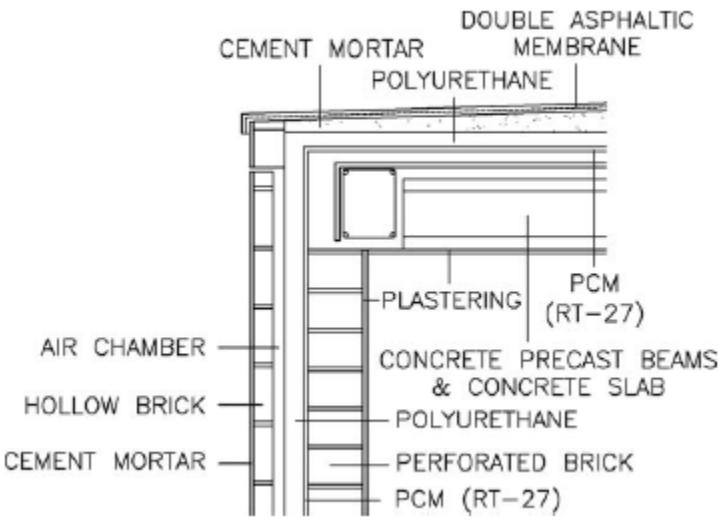

Figure 1: Cross section of the sample using PCM (Castell et al., 2010)

Figure 2: Temperature in brick wall without PCMs (upper) and with PCM (lower) (Zhang et al., 2011)

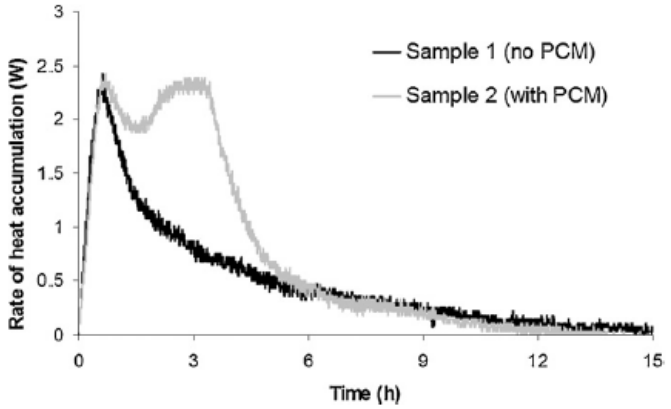

Figure 3: Rate of heat accumulation in sample with/without PCM(de Gracia et al., 2011)

Bontemps et al. (Bontemps et al., 2011) conducts a study of impregnation PCM into inner glass walls using twin cells. Glass is useful in cold months of the year as it helps to absorb the maximum thermal energy from sunlight. However, during hot months glass walls capture the solar heat and create uncomfortable thermal condition inside the room. So the study is implemented in May, June and July, when the solar radiation is the highest in a year and three typical PCMs: fatty acid, paraffin and salt hydrate are used. The results demonstrate that a reduction of 3 to 50C is observed when PCM is impregnated into the separating wall and further improvement can be made in the association with ventilating system during nighttime. With the aid of information technology, Sundaram et al. (Sundaram et al., 2010) does an investigation on PCM effect in passive cooling with ventilation for buildings in hot regions (figure 4). It is revealed that PCM charges during daytime and maintain the temperature in a comfort range. Moreover, comparing to traditional HVAC system, passive cooling with PCM reserves 14 tons of carbon emission each year.

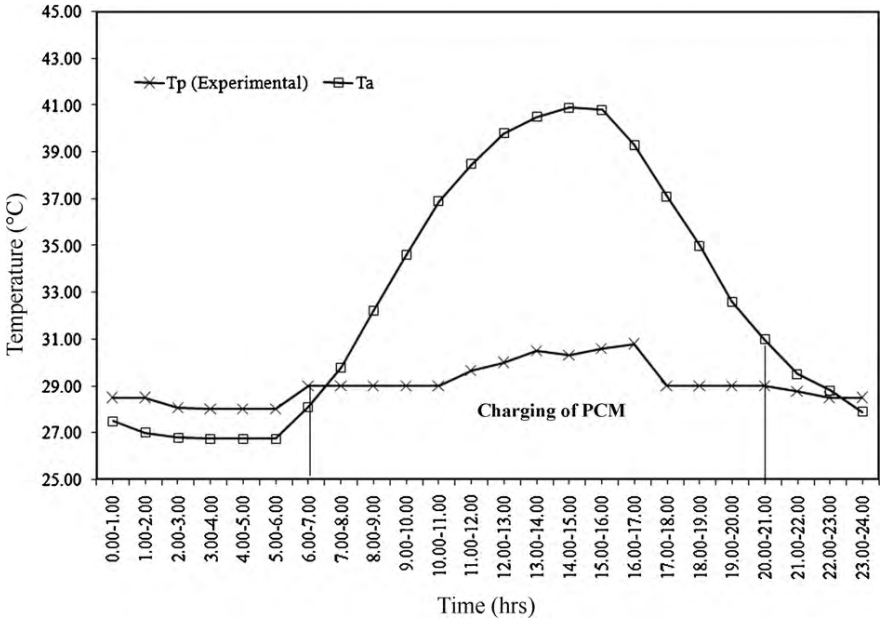

Figure 4: Temperature of ambient (Ta) and PCM (Tp) (Sundaram et al., 2010)

2.3. Appraise of PCM

Diverse types of PCM have been invented and applied in the building envelopes. A deep understanding on the nature and embodied behavior of each type is necessary in order to employ PCM with it utmost productiveness. Phase change materials can be classified chemically into 3 categories: inorganic and organic substance.

Inorganic PCM, which includes water, hydrated salt and its composition, is the first known material for latent heat thermal energy storage. Most hydrated salts express comparatively high latent heat of fusion, comparative thermal conductivity, non-flammability and competitive price. High latent heat of fusion intimates better capacity of heat storage, thus less PCM is required to achieve the same magnitude of heat storage. However, supercooling, together with leakage and degradation over time of cycling are the crucial obstacles of inorganic PCM. The cause of supercooling is the lack of the

first seed for the crystallization of the salt. When the temperature is below the freezing point, the solidification cannot take place and results in the lag of temperature respond.

In the opposite, most organic PCMs have little or no supercooling, as they possess self-nucleating behavior. Other advantages are high chemical stability, small volume change during phase transition, non-toxicity, non-corrosion by metal and minor thermal degradation with time (Li and Wu, 2011). Small volume change is crucial when impregnating into constructive material without adding any reduction in the strength and load bearing of the structure. However, organic PCM often has low thermal conductivity, problem with leakage and flammability. Organic PCMs in turns can be divided into smaller categories of paraffin, fatty acid/ester, glycol and alcohol. Although non-paraffin PCMs usually have higher heat of fusion paraffin, their high cost and the incompatibility of phase change temperature with human thermal comfort (Baetens et al., 2010).

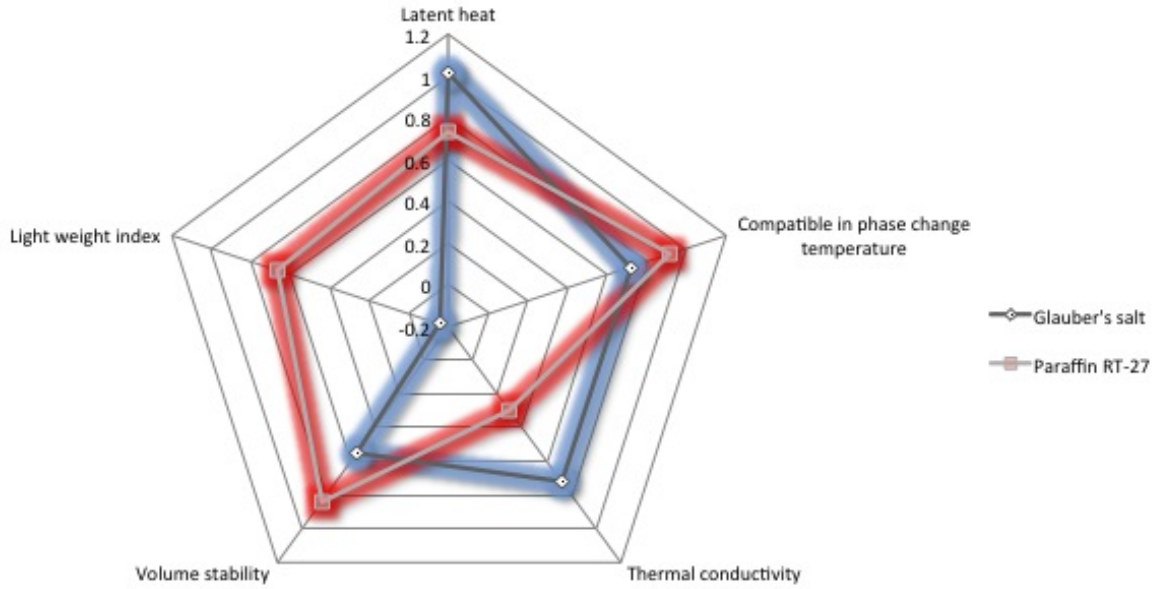

Figure 5: Evaluation of PCMs

Figure 5 offers a critical appraise between inorganic and organic PCM. Glauber's salt (Sharma et al., 2009) (sodium sulphate) – the cheapest and typical hydrated salt for thermal energy storage and paraffin RT-27 are taken into account. The evaluation is based on five factor: (1) latent heat: reflects the heat storage capacity of the material; (2) compatible in phase change temperature: indicates the suitable of the PCM with the thermal comfort; (3) thermal conductivity: expresses the ability of even heat distribution and workability of PCM; (4) volume stability: relates to the steadiness of volume during phase transition; and (5) light weight index: shows the impact of exceed weight of PCM added to concrete structure. As can be seen in this figure, paraffin is a super lightweight material with excellent latent heat, suitable melting point and volume stability compared to Glauber's salt.

However, its thermal conductivity is less than half of hydrated salt, thus causes restriction to the performance of paraffin as a thermal heat storage material. And this remains the utmost drawback of organic PCMs. Another point should be noted that leach is the crucial problem for both inorganic and organic PCMs. Therefore performance enhancement of PCMs relating to leakage and transient heat transfer is necessary and will be discussed in the following sections.

3. Shape-stabilized PCMs

Phase change material is proved to promote the issue of energy conservation in modern buildings by far, but each property and working condition of PCM should be taken into consideration nonetheless. This is crucial to ensure its feasibility in practical application. The cautious selection of PCM seeks for the one with the highest adaption according to 5 criteria as indicated in figure 5. However, even the type of PCM, which can meet those criteria, still has the problem with leakage. It comes from the embodied behavior of PCM as its working condition covers both liquid and solid state. Therefore, the impregnation of PCM into constructive material encounters leaking whenever it is in the liquid phase. Two methods have been investigated recently to address this issue are encapsulation and shape stabilization. In the former, the cell made of rigid and chemically inert material such as polystyrene, high-density polyethylene or ceramic is used to isolate PCM from constructive material and prevent the loss of PCM during operation (Sanchez et al., 2007, Li et al., 2009, Pitie et al., 2011). This article focuses on the application of the shape-stabilizing method.

Shape stabilization is distinguished from encapsulation in the manner of storing PCM. No cells occur with shape stabilization, but materials with high and compatible absorption are used to capture PCM, thus the stability and even distribution of PCM is assured. Higher percentage of PCM can be incorporated in the structure and lower cost is required with this method (Mei et al., 2011, Karaipekli and Sarı, 2009). In recent patents relating to PCM, three types of materials are employed to stabilize the shape of PCM, which are natural mineral, cementitious material, expanded graphite and polymeric material.

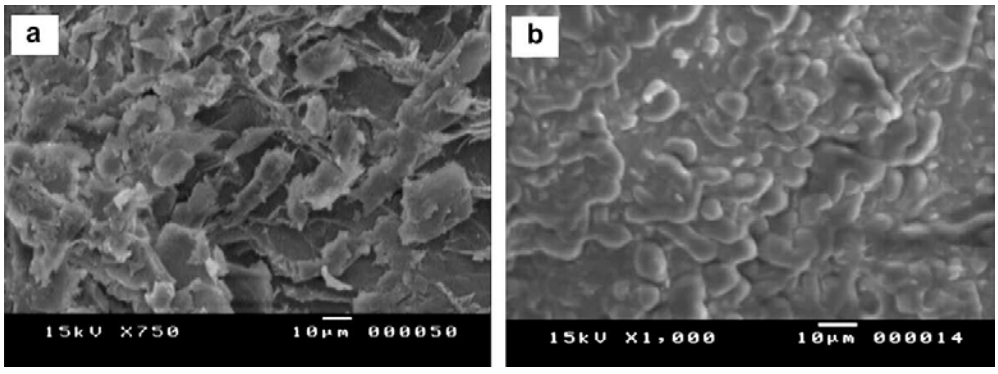

Figure 6: SEM images of vermiculite (a) and capric – myristic/vermiculite PCM (b) (Karaipekli and Sarı, 2009)

Natural mineral is used because it has porous structure, non-toxic, affordable price and lightweight. This material is preferred with non-paraffin PCM. Vermiculite, a natural mineral is used with the

eutectic compound of capric - myristic acid with the aid of vacuum impregnation (Karaipekli and Sarı, 2009). SEM images of vermiculite and in figure 6 indicate that all the pores of vermiculite are stocked by the eutectic PCM. The maximum proportion of capric – myristic PCM in this composite is 80%, which is relatively high. Mei et al. (Mei et al., 2011) incorporates halloysite nanotube, alumino - silicate clay mineral, with capric acid, which melts at 290C. 60% of capric acid is absorbed in halloysite nanotube and no leakage is observed at temperature higher than melting point of capric acid. The upper photo in figure 7 is taken at room temperature while the lower photo is taken at 400C, which is over 100C above the melting point. Sample (a) is pure capric acid and leach is noted at 400C, the other samples with halloysite nanotube remain stable without leakage.

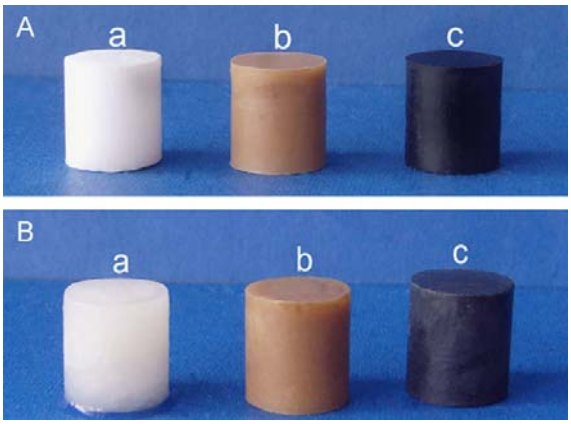

Figure 7: Pure capric acid (a), capric acid/halloysite (b) and capric acid/halloysite/graphite at room temperature (A) and 40^0C (B) (Mei et al., 2011)

The second group of cementitious material includes Portland cement and silicafume. The significance of these materials is that they are compatible with constructive materials like concrete as they both have the properties of pozzolanic active materials. Researches done by Wang et al. (Wang et al., 2011) and Li et al. (Li et al., 2010) demonstrate that shape stabilized function of Portland cement and silicafume is accomplished with the portion of PCM in the composite is up to 90% for silicafume and 50% for Portland cement. In addition, no chemical reaction occurs because the connection between PCM and cementitious materials is based on capillary, surface tension force of hydrogen bonds.

Other strategy of stabilizing PCM is implementing expanded graphite, polymer or the combination of those. Polymeric material is suitable for paraffin because of their similar skeleton. Polyethylene, preferred high-density polyethylene (HDPE), and polypropylene can be embedded. Previously HPDE bottle and HDPE shell is used to encapsulate PCM, but recent studies shows the prospect of HDPE as supporting material for paraffin (Zhang et al., 2010, Cai et al., 2009, Cai et al., 2008). The novel shape-stabilized PCM is prepared by mixing HDPE and paraffin at approximately 1500C, pre-drying is necessary for utmost absorption. Cai et al. (Cai et al., 2009) reveals the excellent distribution of paraffin in HDPE matrix (figure 8) and the reason for this matter is their homologation not the porosity as in the case of natural mineral and cementitious material. The advantages of HDPE compose no chemical reaction, minor impact on thermal storage capacity of paraffin, little shift in phase change temperature. On the other hand, expanded graphite is considered owing to its porous

structure but it is more effective in terms of enhancing the transient heat transfer for PCMs, which is discussed in the fourth section of the article.

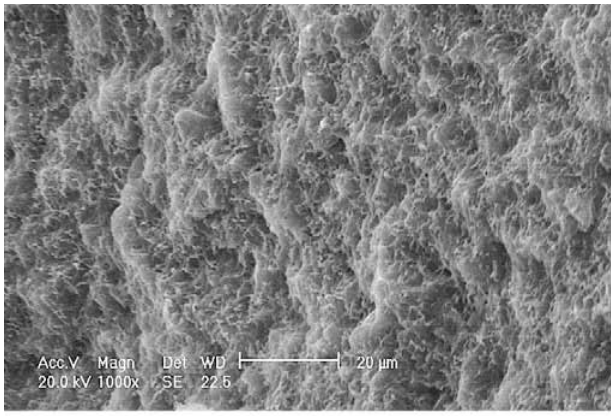

Figure 8: SEM images of paraffin/HDPE (Cai et al., 2009)

4. Enhancement of transient heat transfer for PCMs

In section 2.3, the matter of transient heat transfer of PCMs is mentioned and low transient thermal respond of PCM is caused by its slow thermal conductivity. Even in the case of inorganic PCM, which possesses the thermal conductivity of twice as much as that of organic PCM, this figure is only about 0.5W/m. K. The fatality of slow transient thermal respond is to accompany overheating in the outer layer of PCM as thermal conductivity expresses the capability of the material to impart heat in its volume. When exposed to heat source, i.e. solar radiation, the outer layer of PCM absorbs that heat and convert it into its embodied energy as latent heat. However this layer with low thermal conductivity cannot transfer external heat to the inner layers although the former turns into melting state properly. It is, then, obvious that external heat continues elevating the ouster layer's temperature and vortex motion of this overheated fluid prevents the heat from being transferred more severely. Another point is that only a thin layer on the surface of PCM actually exchanges heat, thus, just this fragment works properly. This results in the dramatic fall in heat storage capacity of PCMs.

Table 1: Thermal conductivity of PCMs and supporting materials

Materials	***Thermal conductivity (W/m. K)***
Glauber's salt	*0.6*
Paraffin RT-27	*0.2*
Alumina (Huang et al., 2006)	*211*
Copper (Jegadheeswaran and Pohekar, 2010)	*400*

Graphite(Prieto et al., 2011)	499
Graphene (Yavari et al., 2011)	4840 - 5300

Therefore, in order to enhance the thermal conductivity of PCMs, several approaches have been attempted. The core of all these approaches is combining highly conductive materials such as metal and graphite with PCMs. Table 1 illustrates the gap between PCMs and these supporting materials. The effect of thermal conductivity of PCM composite (with supporting materials) is not simply the percentage of these materials, but it is proportional to their content and significant results are achieved.

Metal is often employed in the form of: (1) fins and pins; and (2) metal foam. Saha et al. (Saha et al., 2008) embeds aluminum pin and plate fins in PCM and the largest impact of this configuration is with 8% embedded in PCM. However, the use of metal fins and pins confronts with the issue of weight, as this supporting configuration is comparatively heavy, 2.5 times heavier than PCM itself, hence, increases the awareness of load bearing for the thermal storage system. In the second option, metal foam, a highly porous structure, can store PCM in its pores. The advantage of this method is heat transfer by conduction is prevailed due to the fact that conductive metal is the continuous phase in the composite, then, heat is imparted inside the volume of the composite by metal not PCM. Zhou and Zhao (Zhou and Zhao, 2011) incorporate copper foam with paraffin and hydrated salt. A double and triple increase in thermal conductivity as well as a quarter and a third of melting time of paraffin and hydrated salt respectively is observed.

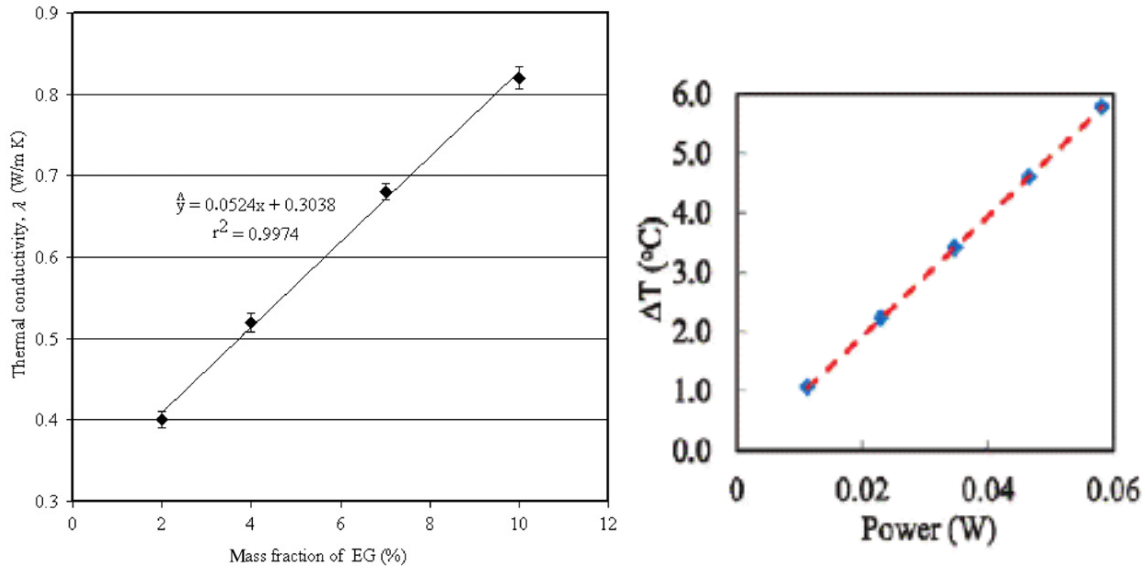

Figure 9: Thermal conductivity of PCM composite with EG (left) and graphene (right) (Sarı and Karaipekli, 2007, Yavari et al., 2011)

Graphite has high thermal conductivity even in comparison with metal. The principle of using graphite is almost the same as for porous metal foam. Graphite can be applied in the form of: graphite foam, expanded graphite (EG) and nano graphite. They all have very high porosity, especially the last

one. Porosity is important in this case because it's in correlation with the surface area and the issue of lightweight material. Figure 9 (Sarı and Karaipekli, 2007, Yavari et al., 2011) shows the effect of expanded graphite and graphene on the thermal conductivity of PCMs. It can be seen that with the incorporation of less than 2.5% graphitic material, the thermal conductivity is doubled. Graphitic material is also superior when comparing metal in terms of conversion phase change enthalpy. Yavari and Yu (Yavari et al., 2011) reveal that to achieve the same enhancement of thermal conductivity as with 4% of graphene, 45% of silver metal should be employed. And the reduction in phase change enthalpy is 15% with graphene and 50% with silver metal.

5. Conclusions

Thermal energy storage by latent heat with PCM is a convincing approach for energy conservation in buildings. Its critical contribution expresses in the three aspects: shortening the usage of non-renewable energy as electricity, coal and fuel oil; shifting the peak of energy demand to an appropriate point; and utilizing green energy – solar radiation. Therefore, modern buildings and construction can meet the urgent requirement of reducing carbon footprint in their embodied structures.

At this period, both organic and inorganic PCM is facing with the issue of leach and transient heat transfer, which hinders its proper performance. Among available methods, graphite especially graphene offers a promising trend for PCM. However, further studies on transient heat respond of the composite as well as the interaction between PCM and the substrate is recommended to implement.

References

BAETENS, R., JELLE, B. P. & GUSTAVSEN, A. 2010. Phase change materials for building applications: A state-of-the-art review. *Energy and Buildings,* 42**,** 1361-1368.

BOJNEC, S. & PAPLER, D. 2011. Economic Efficiency, Energy Consumption and Sustainable Development. *Journal of Business Economics and Management,* 12**,** 353-374.

BONTEMPS, A., AHMAD, M., JOHANNÈS, K. & SALLÉE, H. 2011. Experimental and modelling study of twin cells with latent heat storage walls. *Energy and Buildings,* 43**,** 2456-2461.

CAI, Y., WEI, Q., HUANG, F. & GAO, W. 2008. Preparation and properties studies of halogen-free flame retardant form-stable phase change materials based on paraffin/high density polyethylene composites. *Applied Energy,* 85**,** 765-775.

CAI, Y., WEI, Q., HUANG, F., LIN, S., CHEN, F. & GAO, W. 2009. Thermal stability, latent heat and flame retardant properties of the thermal energy storage phase change materials based on paraffin/high density polyethylene composites. *Renewable Energy,* 34**,** 2117-2123.

Canada: Energy report. 2010. *Energy Industry Report: Canada***,** 9-20.

CASTELL, A., MARTORELL, I., MEDRANO, M., PÉREZ, G. & CABEZA, L. F. 2010. Experimental study of using PCM in brick constructive solutions for passive cooling. *Energy and Buildings,* 42**,** 534-540.

DE GRACIA, A., BARRENECHE, C., FARID, M. M. & CABEZA, L. F. 2011. New equipment for testing steady and transient thermal performance of multilayered building envelopes with PCM. *Energy and Buildings*.

ENERGY CONSUMPTION. 2011a. *Global Energy Market Research: Germany***,** 23-28.

ENERGY CONSUMPTION. 2011b. *Global Energy Market Research: Australia***,** 18-23.

Energy Consumption by Sector. 2011c. *Monthly Energy Review***,** 21.

ESAM M, A. 2008. Thermal analysis of a building brick containing phase change material. *Energy and Buildings,* 40**,** 351-357.

HUANG, M. J., EAMES, P. C. & NORTON, B. 2006. Phase change materials for limiting temperature rise in building integrated photovoltaics. *Solar Energy,* 80**,** 1121-1130.

JEGADHEESWARAN, S. & POHEKAR, S. D. 2010. Exergy analysis of particle dispersed latent heat thermal storage system for solar water heaters. *Journal of Renewable & Sustainable Energy,* 2**,** 023105.

KARAIPEKLI, A. & SARI, A. 2009. Capric–myristic acid/vermiculite composite as form-stable phase change material for thermal energy storage. *Solar Energy,* 83**,** 323-332.

KUZNIK, F. & VIRGONE, J. 2009. Experimental investigation of wallboard containing phase change material: Data for validation of numerical modeling. *Energy and Buildings,* 41**,** 561-570.

LI, H., LIU, X. & FANG, G. 2010. Preparation and characteristics of n-nonadecane/cement composites as thermal energy storage materials in buildings. *Energy and Buildings,* 42**,** 1661-1665.

LI, J., XUE, P., HE, H., DING, W. & HAN, J. 2009. Preparation and application effects of a novel form-stable phase change material as the thermal storage layer of an electric floor heating system. *Energy and Buildings,* 41**,** 871-880.

LI, M. & WU, Z. 2011. Preparation and Performance of Highly Conductive Phase Change Materials Prepared with Paraffin, Expanded Graphite, and Diatomite. *International Journal of Green Energy,* 8**,** 121-129.

MEI, D., ZHANG, B., LIU, R., ZHANG, Y. & LIU, J. 2011. Preparation of capric acid/halloysite nanotube composite as form-stable phase change material for thermal energy storage. *Solar Energy Materials and Solar Cells,* 95**,** 2772-2777.

PITIE, F., ZHAO, C. Y. & CACERES, G. 2011. Thermo-mechanical analysis of ceramic encapsulated phase-change-material (PCM) particles. *Energy & Environmental Science,* 4**,** 2117-2124.

PRIETO, R., MOLINA, J. M., NARCISO, J. & LOUIS, E. 2011. Thermal conductivity of graphite flakes-SiC particles/metal composites. *Composites Part A: Applied Science and Manufacturing,* 42**,** 1970-1977.

SAHA, S. K., SRINIVASAN, K. & DUTTA, P. 2008. Studies on optimum distribution of fins in heat sinks filled with phase change materials. *JOURNAL OF HEAT TRANSFER-TRANSACTIONS OF THE ASME,* 130.

SANCHEZ, L., SANCHEZ, P., DE LUCAS, A., CARMONA, M. & RODR√≠GUEZ, J. 2007. Microencapsulation of PCMs with a polystyrene shell. *Colloid & Polymer Science,* 285**,** 1377-1385.

SARI, A. & KARAIPEKLI, A. 2007. Thermal conductivity and latent heat thermal energy storage characteristics of paraffin/expanded graphite composite as phase change material. *Applied Thermal Engineering,* 27**,** 1271-1277.

SHARMA, A., TYAGI, V. V., CHEN, C. R. & BUDDHI, D. 2009. Review on thermal energy storage with phase change materials and applications. *Renewable and Sustainable Energy Reviews,* 13**,** 318-345.

SUNDARAM, A. S., SEENIRAJ, R. V. & VELRAJ, R. 2010. An experimental investigation on passive cooling system comprising phase change material and two-phase closed thermosyphon for telecom shelters in tropical and desert regions. *Energy and Buildings,* 42**,** 1726-1735.

WANG, Y., XIA, T. D., ZHENG, H. & FENG, H. X. 2011. Stearic acid/silica fume composite as form-stable phase change material for thermal energy storage. *Energy and Buildings,* 43**,** 2365-2370.

YAVARI, F., FARD, H. R., PASHAYI, K., RAFIEE, M. A., ZAMIRI, A., YU, Z., OZISIK, R., BORCA-TASCIUC, T. & KORATKAR, N. 2011. Enhanced Thermal Conductivity in a Nanostructured Phase Change Composite due to Low Concentration Graphene Additives. *The Journal of Physical Chemistry C,* 115**,** 8753-8758.

ZHANG, C., CHEN, Y., WU, L. & SHI, M. 2011. Thermal response of brick wall filled with phase change materials (PCM) under fluctuating outdoor temperatures. *Energy and Buildings*.

ZHANG, P., SONG, L., LU, H., WANG, J. & HU, Y. 2010. The influence of expanded graphite on thermal properties for paraffin/high density polyethylene/chlorinated paraffin/antimony trioxide as a flame retardant phase change material. *Energy Conversion and Management,* 51**,** 2733-2737.

ZHOU, D. & ZHAO, C. Y. 2011. Experimental investigations on heat transfer in phase change materials (PCMs) embedded in porous materials. *Applied Thermal Engineering,* 31**,** 970-977.